Development of the One-Sided Nonlinear Adaptive Doppler Shift Estimation Techniques

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ABSTRACT

The new development of a one-sided nonlinear adaptive shift estimation technique (NADSET) is introduced. The background of the algorithm and a brief overview of NADSET are presented. The new technique is applied to the wind parameter estimates from a 2-μm wavelength coherent Doppler lidar system called VALIDAR located in NASA Langley Research Center in Virginia. The new technique enhances wind parameters such as Doppler shift and power estimates in low Signal-To-Noise-Ratio (SNR) regimes using the estimates in high SNR regimes as the algorithm scans the range bins from low to high altitude. The original NADSET utilizes the statistics in both the lower and the higher range bins to refine the wind parameter estimates in between. The results of the two different approaches of NADSET are compared.

Keywords: Coherent lidar, NADSET, VALIDAR, wind measurement

1. INTRODUCTION

The lidar system VALIDAR (validation lidar) is a 2-μm coherent Doppler lidar system located in NASA Langley Research Center in Hampton, Virginia. The application of VALIDAR ranges from wind profiling to CO_2 measurements. Its data processing software can acquire live lidar returns at a trigger rate of $5 - 10$ Hz, estimate a variety of wind parameters, display the results, and archive them according to user preferences. Due to the large amount of data being acquired, it is critical for the system to be able to handle both the amount of data and the speed for data processing and display. The data processing algorithm has been evolving to perform not only simple and basic data processing such as fast Fourier transforms (FFTs) but highly sophisticated data manipulation algorithms.

Among many of such advanced algorithms is Nonlinear Adaptive Doppler Shift Estimation Technique (NADSET). Its nonlinear adaptive algorithm enhances the quality of the Doppler shift estimates, which affect the other wind profile parameters such as power, wind speed, and wind direction. NADSET is effective in low Signal-to-Noise-Ratio (SNR) regimes, especially when they are between relatively strong SNR range bins. This paper introduces an evolved version of NADSET that does not depend on strong SNR on both sides of a range interval of interest with low SNR.

This paper is organized as follows: a brief discussion about VALIDAR is presented in Section 2. Section 3 covers the review of the original NADSET. Section 4 discusses the latest NADSET called LS-NADSET (Left-Sided NADSET). The comparison of NADSET and LS-NADSET is also presented in Section 4. The last section is the conclusion of the latest development and presents a future research direction.

2. VALIDATION LIDAR – A COHERENT DOPPLER LIDAR

The first generation of the system was launched in 2002 for ground-based wind profiling. The optical equipment bench and the data acquisition and analysis station are housed in a trailer for mobility. The laser beam is guided through a scanner that is mounted on the top of the trailer, which is controlled by the data acquisition and analysis software through a RS-232 connection. As the scanner rotates to a user-defined set of look directions, a number of laser pulses

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are emitted through it, and their echoes are recorded and analyzed. The current processing system consists of a compact PCI chassis with a data acquisition module Acqiris DC240, a digital signal processing module BittWare ADSP-21160M Hammerhead, and a CPU module PEP CP603. The chassis has eight slots and each module occupies one. The lidar returns are sampled at 500 MHz with 8-bit resolution, being triggered by an external train of TTL pulses at 5-10 Hz. The sampled data by Acqiris DC240 are transferred to ADSP-21160M that has eight DSP processors via bus mastering at the rate of 90 Mbyte/sec for upload and 30 Mbytes/sec for download. The frequency spectra are computed on the eight DSP chips in parallel and the results are transferred back to the host. The data processing program is written in Visual C++ with the GUI libraries supplied by National Instruments. The current system is capable of real-time data processing while lidar returns are being acquired, and four wind parameters are estimated such as power spectra, Doppler shift, wind direction, and wind speed. The system can archive the output estimates to a disk via a user input. A variety of data analysis and algorithm development studies can be found in [2-4, 6-9].

As laser dynamics may occasionally create a pulse that is not of a single-frequency spectrum, each lidar return is examined for its eligibility for data processing by estimating the frequency at the maximum power in the samples at the beginning of the return such as the first 1024 samples, and confirming that it is within a user specified range. The current default range is from 95 MHz to 115 MHz, since the nominal intermediate frequency is optically set at 105 MHz. If the maximum power frequency falls within this range, the rest of the lidar return time series are divided into range bins containing nominal number of samples. The current VALIDAR data processing algorithm collects 512 samples with 50% overlap in the two adjacent range bins. Then, the FFT is applied to the time series in each range bin. The same procedure repeats with the entire collection of lidar returns. Once the FFTs of each range bin from the lidar returns that have passed the zero Doppler test are obtained, the spectra are adjusted by the frequency difference between the maximum power of the lidar return that has passed the zero Doppler test for the first time and that of the ones afterwards. This is called zero Doppler normalization and the resulting frequency adjusted FFTs are used to compute Doppler shift, wind speed, and wind direction.

Fig. 1. The VALIDAR trailer located in NASA Langley Research Center, Hampton, VA, USA.

3. NONLINEAR ADAPTIVE DOPPLER SHIFT ESTIMATION TECHNIQUE (NADSET)

The NADSET algorithm [5] monitors the quality of Doppler shift estimates – one of the four wind parameters estimated by the data processing software of VALIDAR – using seven parameters among which four are user specific and the rest data dependent, and adjusts the Doppler shift estimates based on the seven parameters. This will consequently affect the estimates of power distribution, wind speed, and wind direction. The first stage of NADSET is to identify the range intervals where the SNR levels are significantly lower than their range neighborhood. In such range intervals, the

Doppler shift estimates typically fluctuate showing unstable tendency. Once such intervals are identified, NADSET computes the statistics of the Doppler shift estimates in strong SNR range bins. The statistics along with user specific NADSET input parameters are applied to the Doppler shift estimates in the low SNR range bins in order to adjust them conforming to the estimate behavior in the adjacent strong SNR range bins. The authenticity of NADSET is established by a meteorological interpretation of long-period lidar return data [5].

NADSET bases its algorithm on relatively strong SNR range intervals and works effectively if the SNR level in both sides of a range interval of interest for enhancement is high. The SNR, however, deteriorates exponentially as the range increases, and its effectiveness diminishes accordingly. Consequently, the credibility of the enhancement reduces as well. The latest development of NADSET is to compensate such adverse situations, and adjust the Doppler shift estimates in low SNR range bins based on the statistics of Doppler shift estimates in lower range bins with high SNR. By removing the dependency on the right-side range bins (farther ranges), the latest development returns more reliable wind parameter estimates, especially in far ranges.

4. LEFT-SIDED NADSET (LS-NADSET) AND NADSET

The latest development of NADSET algorithm is called Left-Sided NADSET (LS-NADSET) since it only depends on the statistics of Doppler shift estimates in close ranges in order to improve those in far ranges. It is worth noting that the original NADSET works superior to LS-NADSET in strong SNR regimes. Therefore, the hybrid of NADSET and LS-NADSET is implemented over the entire range bins. When the signal level is strong, NADSET operates and LS-NADSET otherwise, toward the far end of range bins. Figure 2 shows the Doppler shift estimates from the data processing software of VALIDAR in a thin line and the application of NADSET in a thick line. Similarly, figure 3 compares the Doppler shift estimates between with and without LS-NADSET in a thick and a thin lines, respectively, and it shows the result of LS-NADSET applied to the entire range bins in order to see the difference in operation between NADSET and LS-NADSET.
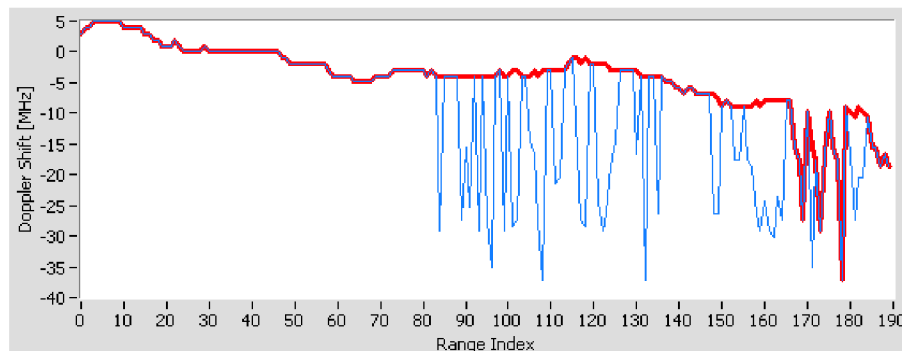

Fig. 2. With and without NADSET on the Doppler Shift estimates from VALIDAR. The thin line represents the estimates from the data processing software of VALIDAR without NADSET and the thick line with NADSET.

Figures 2 and 3 show that NADSET returns more improvement in Doppler shift estimates in lower range bins – more stable behavior of Doppler shift estimates. LS-NADSET does eliminate the rapid oscillation of Doppler shift estimates in lower range bins, but the results still show greater variation than those from NADSET. However, in far ranges such as range bin indices 165 and beyond, NADSET fails to identify the gradual decreasing trend in Doppler shift estimates whereas LS-NADSET follows such tendency. This shows that the combination of NADSET and LS-NADSET would work effectively over the entire range bins instead of sole application of either one.
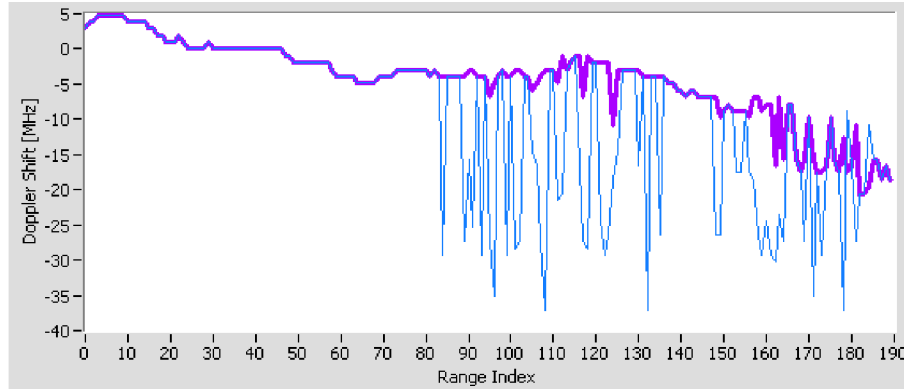
Fig. 3. With and without LS-NADSET on the Doppler Shift estimates from the data processing software of VALIDAR. The thin line represents the estimates from VALIDAR without NADSET and the thick line with LS-NADSET. Note that LS-NADSET is applied to the entire range bins in order to show the difference between NADSET and LS-NADSET.
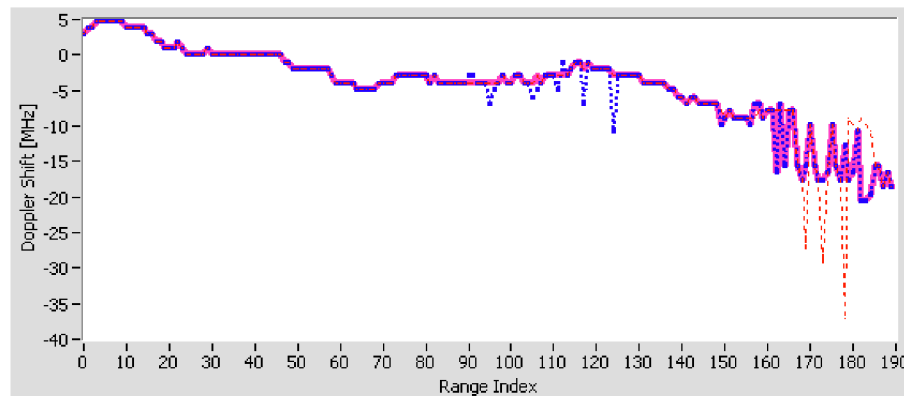

Fig. 4. A comparison of NADSET, LS-NADSET, and the hybrid of both. The dotted line in range bin indices 90 − 130 is LS-NADSET showing its vulnerability in close ranges, and the dotted line around 165 − 190 is NADSET showing its vulnerability in far ranges. The thick line is the hybrid of both showing the optimal operation.

Figure 4 is the comparison of NADSET, LS-NADSET, and the hybrid of both. The dotted line with square dots is the result of LS-NADSET and the dotted line is that of NADSET. In the figure, LS-NADSET shows its vulnerability in close ranges while NADSET shows its vulnerability in far ranges. By combining the both, however, the new Doppler shift estimates are far improved than the original estimates, which are shown in thick line in figure 4.

Figure 5 illustrates the range intervals that are identified by LS-NADSET and the trend of decrease in Doppler shift estimates in each interval. There are a total of four intervals and LS-NADSET oversimplified the tendency in the second interval. Such oversimplification can be eliminated by NADSET since the Doppler shift estimates in the bin indices 110 − 125 are situated between strong SNR range bins both to the left and to the right of this interval. Another case of oversimplification is demonstrated in figure 6. In this case, it seems that there should not be a decreasing trend in the first interval while LS-NADSET attempts to adjust the Doppler shift estimates. Those two figures support the strategy of combining NADSET and LS-NADSET appropriately based on the SNR level in range bins.
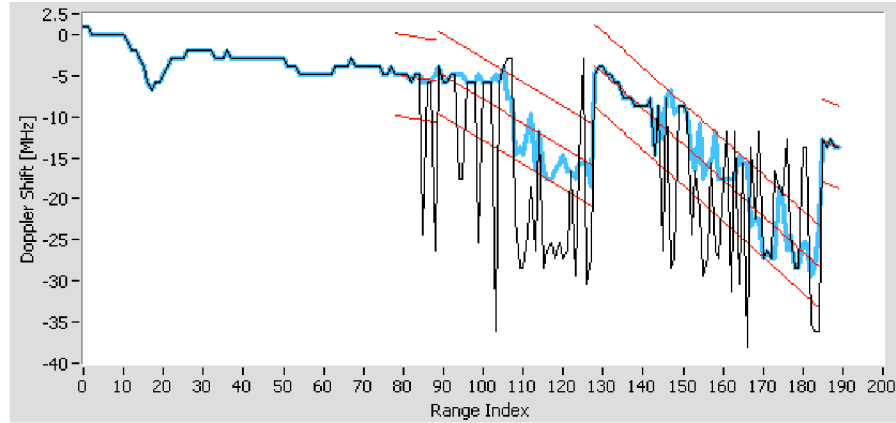
Fig. 5. Intervals identified by LS-NADSET and the results of LS-NADSET. The lidar returns from the first look direction acquired on February 25, 2009 in Maryland, USA is shown in this figure.
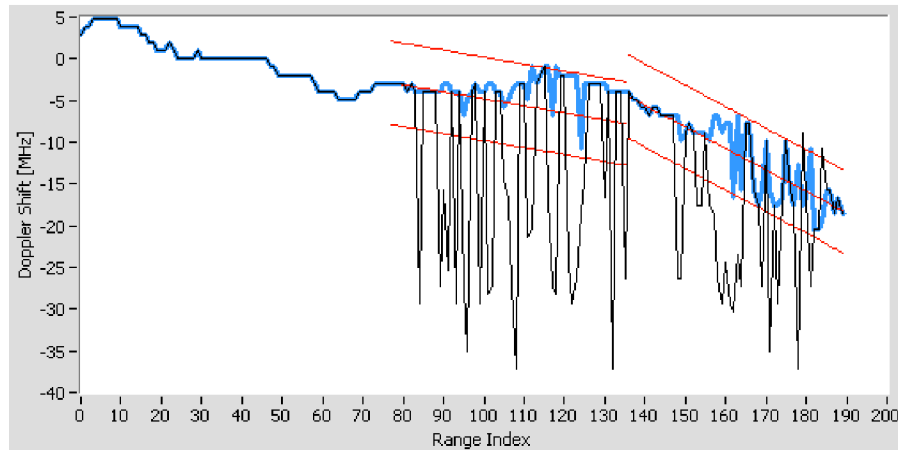

Fig. 6. Intervals identified by LS-NADSET and the results of LS-NADSET. The lidar returns from the second look direction acquired on February 25, 2009 in Maryland, USA is shown in this figure.

Figure 7 shows weather patterns over an extensive observation period using the original VALIDAR estimates, NADSET, and the hybrid of NADSET and LS-NADSET. The figure uses the lidar returns acquired on February 25th, 2009 in Beltsville, MD, USA [10-12].

The first one in figure 7 shows the wind speed variation during 9:40:03 A.M. – 3:48:15 P.M. The confetti-like display in far altitudes about 5 km and beyond implies unstable wind speed estimates due to low SNR. The second one is the result of NADSET. It shows significant improvement in altitudes up to about 9 km and even beyond occasionally. NADSET reveals hidden transition of wind speed that was not visible in the original estimates (first figure). It should be noted, however, that the results of NADSET in far altitudes can be the result of oversimplification as shown previously, and LS-NADSET works more effectively near the far end in altitude. The third figure displays more distinctively the variation of wind speed near 10 km showing a less confetti-like display since LS-NADSET is applied near 10 km while NADSET is applied lower than 10 km.
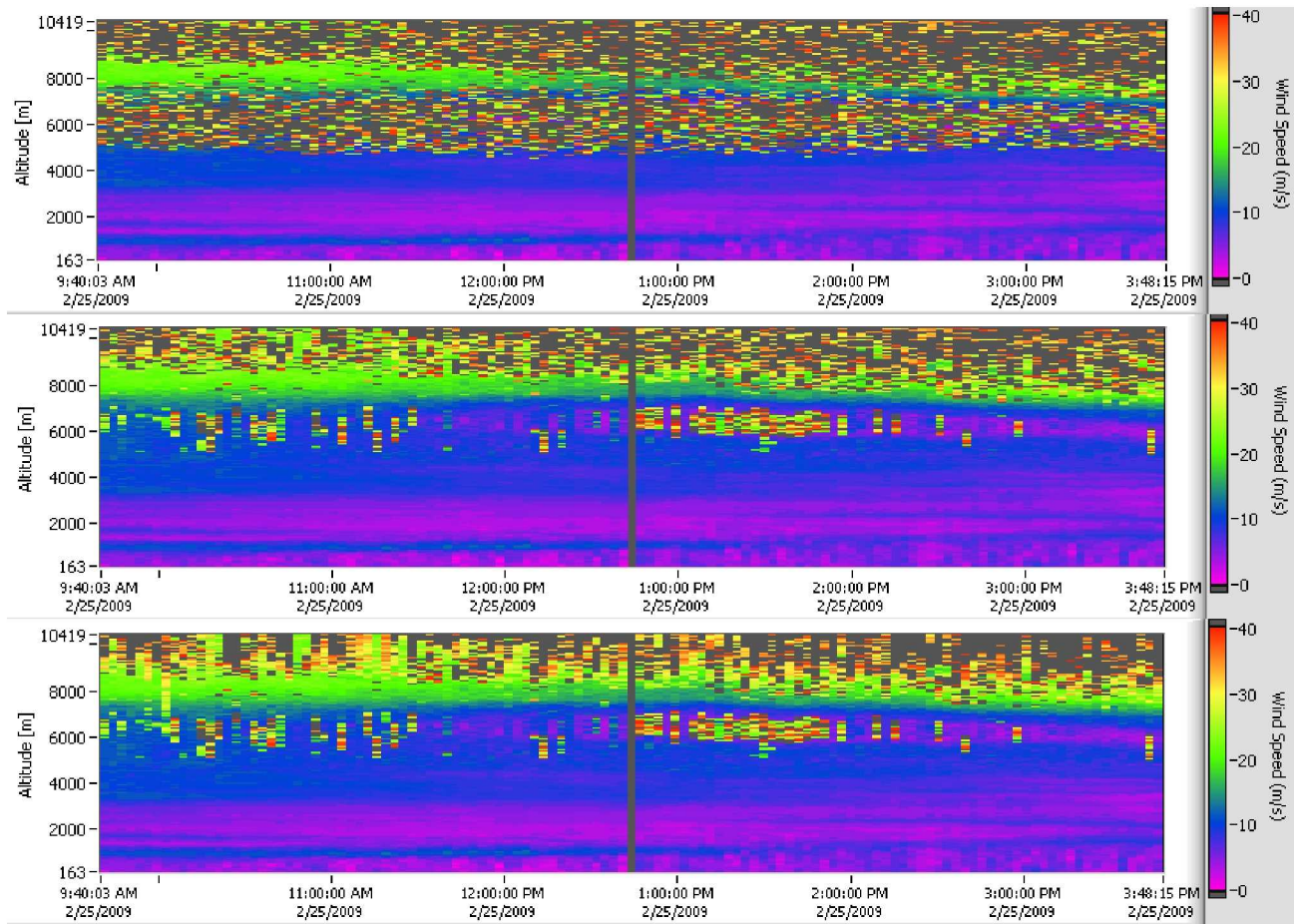
Fig. 7. Weather pattern displays for an about 6-hour observation period. The first one is the original estimates. The second one is the result of NADSET and the third is the result of hybrid of NADSET and LS-NADSET. It shows that NADSET is effective in low altitude where the SNR is high and LS-NADSET in low SNR altitudes.

5. CONCLUSION

The development of the latest NADSET is introduced. Since NADSET depends the Doppler shift estimates in strong SNR range bins, its effect may not be credible if a target range interval is not situated between two strong SNR range bins. Consequently, the enhanced Doppler shift estimates in far ranges may become oversimplified. To complement NADSET, Left-Sided NADSET (LS-NADSET) is developed. Its influence is shown to be credible and effective where NADSET tends to oversimplify Doppler shift estimates, especially when the SNR level is low. LS-NADSET depends on near range statistics where SNR is large, and enhances the quality of wind parameters in far ranges. The comparison of weather patterns over a long observation haul shows that NADSET works effectively in low altitudes and LS-NADSET does in high attitudes. The credibility of each technique is authenticated by meteorological interpretation of the results. The best results are obtained by combining both NADSET and LS-NADSET in order to cover both high and low SNR range bins. Both NADSET and LS-NADSET implement highly sophisticated and intelligent nonlinear algorithms, which identify the intervals where Doppler shift estimates can be improved in different weather scenarios. More intelligence will be integrated into the current development as more variety of weather patterns is investigated.

ACKNOWLEDGMENT

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